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Gamma Ray Measurements at OMEGA with the Newest Gas Cherenkov Detector “GCD-3”

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Abstract. Initial results from the newest Gas Cherenkov Detector (GCD-3) are reported demonstrating improved performance over previous GCD iterations. Increased shielding and lengthening of the Cherenkov photon optical path have resulted in a diminished precursor signal with increased temporal separation between the precursor and the primary DT Cherenkov signal. Design changes resulted in a measured GCD-3 sensitivity comparable to GCD-1 at identical 100 psia CO₂ operation. All metal gasket seals and pressure vessel certification to 400 psia operation allow for a GCD-3 lower Cherenkov threshold of 1.8 MeV using the fluorinated gas C₂F₆ as compared to the 6.3 MeV lower limit of GCD-1 and GCD-2. Calibration data will be used to benchmark GEANT4 and ACCEPT detector models. The GCD-3 acts as a prototype for the Super GCD being fielded at the National Ignition Facility (NIF) as part of the National Diagnostics Plan and will be installed at NIF in early 2016.

1. Introduction

The newest Gas Cherenkov Detector (GCD-3) [1,2,3] was initially fielded in mid-2014 at the Laboratory for Laser Energetics Omega laser facility and has since provided gamma ray measurements for a variety of experimental campaigns. The GCD-3 incorporates significant improvements over the earlier GCD-1 and GCD-2 models and acts as a prototype for the “Super GCD”, one of eight “Transformative Diagnostics” to be installed at the National Ignition Facility (NIF) as part of the National Diagnostic Plan [4]. A diagram of the GCD-3 and the principles of detector operation is shown in figure 1.

Gamma rays produced during Inertial Confinement Fusion (ICF) implosions provide important information about fusion burn and the imploded capsule conditions. Typical implosions utilizing deuterium-tritium (DT) fuel generate high energy (up to 16.75 MeV) DT fusion gamma rays that provide a diagnostic signature directly related to the temporal shape and duration of the fusion burn profile. In addition, primary DT neutron interactions with capsule materials generate gamma rays that contain information about the areal density (ρR) of the ablator near the time of peak fusion burn.

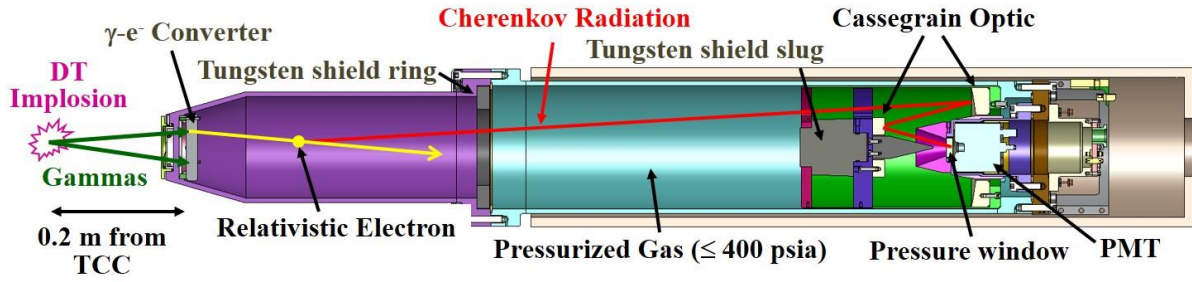


Figure 1. The GCD-3 converts gamma rays into Compton electrons, which generate Cherenkov photons inside of the pressurized gas cell. The Cherenkov photons are then focused onto a photomultiplier tube (PMT) using a Cassegrain optic.

2. GCD-3 Design Improvements

2.1. Optical Path Lengthening and Enhanced Shielding

Several improvements to the GCD-3 design were made to mitigate the impact of the “precursor” signal, which is caused by gamma rays that penetrate or bypass the tungsten shielding and interact directly with the pressure window or photomultiplier tube (PMT). First, the distance between the front of the detector and the primary Cassegrain reflector optic was increased by approximately 4 cm such that the time between the precursor and the Cherenkov signal was increased by ~ 0.25 ns. This additional time difference ensures that the tail end of the precursor signal does not overlap with the rising edge of the Cherenkov signal. As shown in figure 2, the GCD-1 precursor overlaps significantly with the primary gamma peak whereas the temporal separation between the GCD-3 precursor and the primary signal is large enough that the precursor signal completely returns to baseline prior to primary signal onset. The impact of the precursor can be very important for measurements where the primary gamma signals are of the same strength or are weaker than the precursor signal (e.g. at high Cherenkov energy threshold).

GEANT4 simulations indicated that a ring of hevimet tungsten-alloy (92.5% W, 5.25% Ni, 2.25% Fe chosen for its high density and machinability) placed just behind the front flange, as shown in figure 1, would reduce the amplitude of the precursor signal. The hevimet ring shields against diverging gamma rays that might strike the walls of the vessel behind the front flange and subsequently scatter into a trajectory that bypasses the central hevimet slug that shields the PMT from direct-shine gammas. While the hevimet ring reduces the number of Cherenkov photons that pass the front flange, the GCD-3 utilizes a larger diameter gamma-to-electron converter, larger gas volume and improved optical collection such that the detector sensitivity (integrated primary signal) is only $\sim 15\%$ lower than for GCD-1, as

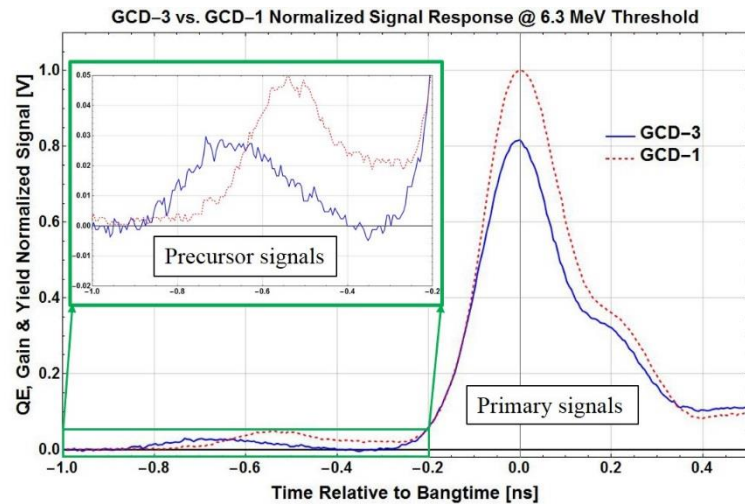


Figure 2. Yield normalized GCD-1 and GCD-3 signals, corrected for differences in PMT quantum efficiency and gain, recorded from Omega shot 77952. The detectors had identical gas fills (100 psia CO₂) and were located the same distance from TCC (20 cm). The GCD-1 (red, dashed line) precursor overlaps with the primary gamma signal while the GCD-3 (blue, solid line) precursor signal completely returns to baseline before the primary signal begins.

illustrated by the relative DT yield normalized signals from Omega shot 77952 shown in figure 2. The larger GCD-3 signal at around 0.4 ns is simply due to differences between the PMTs' unique impulse response shapes in the tail region.

2.2. Metal seals allowing for fluorinated gases at 400 psia

The GCD-1 and GCD-2 detectors utilize rubber O-rings and are pressure rated to an upper limit of 100 psia using non-fluorinated gases. Fluorinated gases such as SF_6 and C_2F_6 have a larger index of refraction than CO_2 at equivalent pressures and are therefore desirable for achieving low Cherenkov threshold energies. However, fluorinated gases can dissociate and release atomic fluorine, which poses a significant corrosive threat to the tritium recovery system at Omega. Stringent leak rate requirements were imposed on the GCD-3 to ensure that fluorine corrosion would not occur, which necessitated the use of all metal seals in place of rubber O-rings. Stainless steel knife-edge flanges were explosion bonded to the aluminum pressure vessel and sealed using copper and/or aluminum gaskets.

A brazed sapphire window separates the pressurized gas volume from the PMT. Initial attempts to install the sapphire window resulted in fracturing of two windows due to heat from the welding operation warping the surrounding metal. Redesigning the window housing resulted in a successful installation of a third backup sapphire window, however this window had not been coated with anti-reflective (AR) coating and the resulting light transmission through the window was predicted to be reduced by about 14%. The sensitivities of the GCD-3 and GCD-1 would be roughly comparable had an AR coated window been used. The GCD-3 has been routinely operated at 400 psia with CO_2 and C_2F_6 , which corresponds to Cherenkov energy thresholds of 2.9 MeV and 1.8 MeV respectively.

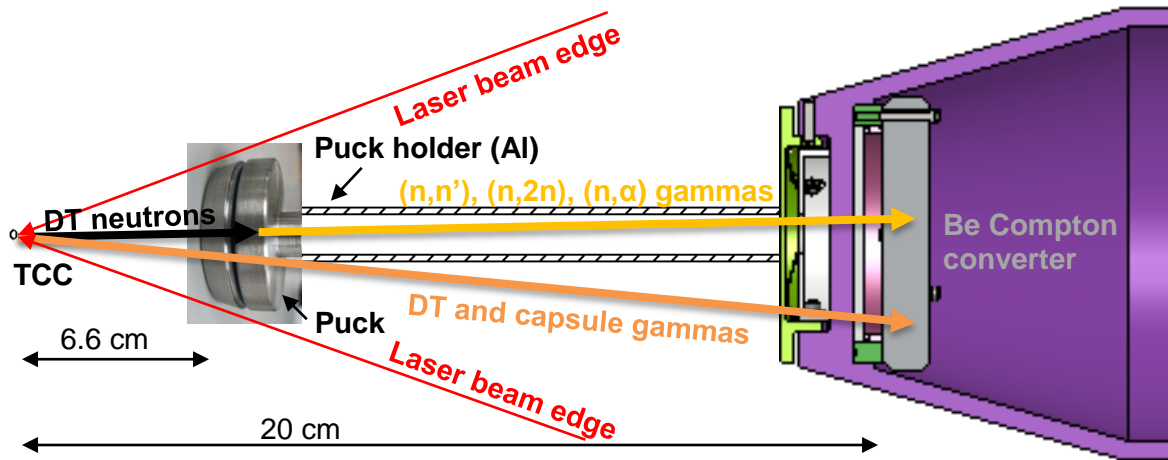


Figure 3. Neutron induced gamma ray studies may be performed using pucks affixed to the front of the GCD-3 (not to scale).

2.3. Neutron induced gamma ray studies using “pucks” mounted on GCD-3

A target, or “puck”, holder consisting of a slender hollow aluminum tube may be affixed to the front of the GCD-3 for neutron induced gamma ray studies on the puck material chosen. 14 MeV DT neutrons interacting with the puck material produce gamma rays that may generate a unique GCD-3 signal if the resulting gamma ray energy is above the Cherenkov threshold energy. This puck signal is separated in time from the primary DT signal by about 1 ns when placed 6.6 cm from target chamber center (TCC), which is determined by the time of flight difference between the prompt (DT and capsule) gamma rays and the DT neutrons. A schematic of the puck assembly on the front of the GCD-3 is shown in figure 3.

Techniques for determining the pR of the unablated plastic or high density carbon (HDC) shell mass at bangtime using previous gas Cherenkov diagnostics have been reported by Hoffman [5,6] and Cerjan [7]. A graphite puck of known density mounted on the front of GCD-3 allows for an in situ calibration of the detector response to 4.44 MeV $^{12}\text{C}(n,n')$ inelastic scatter gamma rays. The puck is also mounted

at other positions around TCC in order to identify the angular distribution of the gamma rays produced, as described previously by Hoffman [8]. A similar glass (SiO₂) puck calibration, complete with angular scan, has been performed to extend the capability of the GCD-3 to determining ablator pR for glass capsule implosions, with results to be published.

3. Future GCD-3 development

In August 2015 the GCD-3 was absolutely calibrated at the High Intensity Gamma-Ray Source (HIGS) at Duke University. The detector response was determined over a wide range of Cherenkov thresholds for different gases by exposing the GCD-3 to well-characterized quasi-mono-energetic gamma rays (Gaussian energy distribution with $\Delta E_\gamma/E_\gamma \sim 5\%$ FWHM) produced by the HIGS free electron laser with gamma ray fluxes between 10^7 and 10^8 gammas/second. Several GCD-3 computational models are being developed using the Monte Carlo codes GEANT4 and ACCEPT, which will be benchmarked against the HIGS data as done previously with the GCD-1 and the Gamma Reaction History (GRH) diagnostics [9].

The GCD-3 will be installed into a 3.9 meter diagnostic well at NIF in early 2016 in preparation for the eventual construction and installation of the “Super GCD”. A specially designed carrier support tube and mounting system has been designed to insert the GCD-3 to various depths within the diagnostic well in order to optimize sensitivity and reduce signal background due to laser plasma interaction (LPI) x-rays. At 3.9 m from TCC, the GCD-3 will be the most sensitive gamma-ray based Reaction History and pR detector fielded at NIF and will enable a wide range of additional gamma-ray studies in support of ICF and discovery science campaigns.

4. Summary

Initial experimental results demonstrate improved GCD-3 performance over earlier GCD designs. Lengthening the Cherenkov photon optical path resulted in a larger temporal separation between the precursor and primary gamma-ray signals. The precursor signal magnitude was also significantly reduced due to improved tungsten shielding. The GCD-3 sensitivity was observed to be $\sim 15\%$ lower than GCD-1 while fielded simultaneously at 100 psia CO₂ on Omega DT implosions, largely due to the use of a back-up sapphire window that lacked AR coating. Metal seals on the GCD-3 allow for 400 psia operation with fluorinated gases and a lower Cherenkov energy threshold limit of 1.8 MeV using C₂F₆. Calibration data obtained at HIGS along with carbon and glass puck signal data will be used to benchmark GEANT4 and ACCEPT detector models that are currently being developed. The GCD-3 will be installed, acting as a prototype for the Super GCD, in a 3.9 meter diagnostic well at NIF in early 2016 to provide high sensitivity pR measurements, reaction history and additional gamma ray measurements in support of the National Diagnostics Plan.

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